Vol. 27 (1996) *ACTA PHYSICA POLONICA B* No 11

NEW RESULTS ON SPIN EFFECTS IN PION-NUCLEUS ELASTIC SCATTERING AND SINGLE-CHARGE EXCHANGE*

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(Received October 9, 1996)

Measurements and theoretical analyses of asymmetries from pion-nucleus scattering and pion-induced single-charge exchange reactions on polarized spin-1/2 nuclei are reviewed.

PACS numbers: 25.80. Dj, 25.10. +s, 24.70. +s

1. Introduction

Since the development of nuclear targets with high polarizations [1–5] many measurements of spin-dependent variables have been done in π-nucleus scattering and reactions on targets of spins 1/2, 1, and 3/2. (See Ref. [6], for example). Polarization variables contain information on the spin-dependent parts of the π-nucleus interaction and of the nuclear ground state and transition densities. This paper reports on the measurements and analyses of asymmetries, A_y, in elastic scattering and single charge exchange reactions (SCX) on polarized spin-1/2 nuclei.

Asymmetry data have been taken at the meson facilities: PSI, TRIUMF, and LAMPF. At PSI, A_y from elastic scattering of π^+ on ^{15}N at the incident energy of 164 MeV were found [7] to be consistent with zero whereas large asymmetries had been predicted by theory [8]. Small values of A_y for elastic scattering of π^+ and π^- from ^{13}C were measured [9, 10] at LAMPF just below (130 MeV) and above (226 MeV) the centroid of the π-nucleon P_{33} (or $\Delta(1232)$) resonance. A_y for the single-charge-exchange (SCX) reaction, ^{13}C(π^-, π^0), were measured at LAMPF at 164 MeV [11]. The agreement with theory [8, 10, 12, 13] is poor for the elastic scattering asymmetries and fair for the SCX [13, 14] data. An experiment [15] on ^{13}C at 100 MeV done at TRIUMF yielded A_y consistent with zero.

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* Presented at the "Meson 96" Workshop, Cracow, Poland, May 10–14, 1996.

Work at TRIUMF using a polarized ^{3}He target [5] revealed [16] very large asymmetries for π^+ scattering at 100 MeV, as predicted by either a simple schematic model or multiple scattering theory [17, 18]. However, these models fail to fit recent π^+ data [19] taken with the TRIUMF target at LAMPF across the Δ resonance (142 MeV, 180 MeV, and 256 MeV). A_y for π^- elastic scattering [20] at 180 MeV and the single-charge-exchange reaction [21], ^{3}He(π^-,π^0)^{3}H, at 200 MeV have also been measured recently.

After reviewing the elastic scattering experiments on ^{15}N and ^{13}C and the attempts to describe these data, this paper discusses the recent work on elastic scattering and SCX on polarized ^{3}He.

2. Theory and experiment

The π-nucleus scattering amplitude for a spin-1/2 target is

$$\mathcal{T}(\theta) = \mathcal{F}(\theta) + \mathrm{i}\mathcal{G}(\theta)\hat{\mathrm{n}} \cdot \vec{\sigma}, \tag{1}$$

where $\vec{\sigma}$ is the nuclear Pauli spin matrix and $\hat{\mathrm{n}} = (\vec{k} \times \vec{k}') \;/\; | \vec{k} \times \vec{k}' |$ is the normal to the reaction plane. $\vec{k}$ and $\vec{k}'$ are the momenta of the incident and scattered pions, respectively. The quantities $\mathcal{F}(\theta)$ and $\mathcal{G}(\theta)$ are, respectively, the complex spin-independent and spin-dependent π-nucleus scattering amplitudes.

The differential cross section, $\mathrm{d}\sigma/\mathrm{d}\Omega$, is given by the sum of $|\mathcal{F}|^2$ and $|\mathcal{G}|^2$. Generally $|\mathcal{G}|^2$ is much smaller than $|\mathcal{F}|^2$ so that $\mathrm{d}\sigma/\mathrm{d}\Omega$ is insensitive to $|\mathcal{G}|^2$ except near the minima of $|\mathcal{F}|^2$. However, A_y is quite sensitive to the spin-dependent part of the π-nucleus interaction because it results from the interference of $\mathcal{F}$ and $\mathcal{G}$ [22]:

$$A_y = \frac{2Im(\mathcal{F} \cdot \mathcal{G}^*)}{(|\mathcal{F}|^2 + |\mathcal{G}|^2)}. \tag{2}$$

Thus, A_y provides information on $|\mathcal{F}||\mathcal{G}| \sin\Phi$, where Φ is the relative phase between $\mathcal{F}$ and $\mathcal{G}$. For a determination of all three variables, $|\mathcal{F}|$, $|\mathcal{G}|$, and Φ, the spin rotation parameter needs to be measured as well. Such experiments require the measurement of the polarization of the struck nucleus, originally polarized in the reaction plane, but are currently not feasible on spin-1/2 nuclei. An ambitious experiment that measures the polarization of recoil deuterons from elastic π^+ scattering on a polarized deuterium target is underway at PSI [23].

The measurement of an asymmetry on a spin-1/2 target is done by taking scattering yields with the target polarized perpendicularly to the reaction plane. Then $A_y = [N_\uparrow - N_\downarrow]/[N_\uparrow p_\downarrow + N_\downarrow p_\uparrow]$ where $N_\uparrow$ and $N_\downarrow$ are the normalized numbers of counts from scattering by target nuclei with their spins oriented parallel (up) or antiparallel (down) with respect to $\hat{n}$. $p_\uparrow$ is the target polarization when the spin is up, and $p_\downarrow$ is the polarization when the spin in down.

Since the pion has no spin, the lowest-order spin-dependence of the π-nucleus interaction in nuclei arises from the spin-orbit ($\boldsymbol{l} \cdot \boldsymbol{s}$) term in the π-nucleon interaction. Here $\boldsymbol{l}$ is the relative angular momentum between the nucleon and the pion and $\boldsymbol{s}$ is the spin of the nucleon. Pion scattering from the unpaired nucleon in an odd-A nucleus gives rise to the spin-dependent amplitude $\mathcal{G}$. The spin-independent part, $\mathcal{F}$, however, results from coherent scattering from all A nucleons and, depending on the details of the elementary π-nucleon amplitudes f and g and the nuclear structure, is expected to be about A times larger than $\mathcal{G}$.

At incident energies near the Δ resonance, second-order contributions to $\mathcal{G}$ may result from spin-dependent effects in the interaction of the intermediate Δ with the residual nucleus [24]. For example, the spin-orbit force ($L \cdot S_\Delta$) between a Δ and the nuclear core [25, 26] is expected to contribute to $\mathcal{G}$. Here L is the angular momentum of the Δ relative to the core and S_Δ is the Δ's spin (3/2). A Δ-nucleon spin-spin force ($S_\Delta \cdot s$) between a Δ and a nucleon has been proposed in order to interpret polarization variables in π-d scattering. However, the validity of the approximations used in Ref. [27] has been questioned [28, 29]. Knowledge of the strength of the spin-dependent (and spin-independent) parts of the Δ-nucleon interaction is needed for tests of meson-exchange [30] and quark models [31] of the baryon-baryon interaction. Since the Δ travels only a couple of fermi before its decay, its interaction with nucleons can only be studied in the nuclear environment.

Theoretical predictions of π-nucleus scattering variables involve two main ingredients: a π-nucleus scattering model and nuclear structure matrix elements from, *e.g.*, a shell model calculation. Frequently the multiple scattering formalism of Ref. [32] (KMT) is applied [8, 33–35]. Ref. [8] for example, solves the Lippmann-Schwinger equation with relativistic kinematics and derives a π-nucleus optical potential in momentum space from the elementary π-nucleon scattering amplitudes. A separable off-shell extrapolation is used and Fermi motion of the nucleons is treated approximately. Other authors use the DWIA and employ the frozen nucleon approximation (*e.g.*, Ref. [13]). Ref. [36, 37] treat Fermi motion exactly, avoid many approximations used by other authors, and give a justification of the energy shift $E_{\rm sh}$ that is often used when evaluating the free π-nucleon scattering amplitude. Calculations of asymmetries have not yet become available in this model. A phenomenological ρ^2 term was introduced [35] in the optical potential to account for true pion absorption. However, this approach to true absorption effects in elastic scattering is probably not valid for very light nuclei.

The other ingredient of a π-nucleus scattering calculation are the nuclear structure matrix elements (or g.s. and transition density amplitudes) $A_{J(KS)}$ [38]. These amplitudes are classified according to J, K, and S which are the total, orbital, and spin angular momentum transfers, respectively. In the p-shell model, there are only two amplitudes with $J(KS) = 0(00)$ and $1(01)$ for the ground state (g.s.) of ^{15}N, and for the ^{13}C(g.s.) there are three amplitudes with $J(KS) = 0(00)$, $1(01)$ and $1(21)$ that contribute to π scattering. Often, the spin-dependent amplitudes from a shell model prediction are renormalized to better reproduce the transverse magnetic form factor, M_{T}, from electron scattering before they are used in π scattering calculations [8].

Two points should be made when comparing analyses of electron and π scattering experiments. First, at incident energies near the Δ resonance, π-nucleus scattering is more sensitive to the isoscalar than the isovector matrix elements whereas M_{T} is predominately isovector. Second, also at energies near the Δ resonance, interactions of the incident pions with the exchange currents in the nucleus are negligible. (See Ref. [39] and references therein). However, meson exchange currents make significant contributions to the electron scattering form factors, especially at large momentum transfer. Thus electrons and pions are complementary probes.

3. Results for *p*-shell nuclei

3.1. Elastic scattering on ^{15}N

Asymmetries for elastic π^+ scattering from ^{15}N at $T_\pi = 164$ MeV were obtained at PSI [7] with a cryogenic ^{15}NH$_3$ target that was polarized to about 15% using the dynamic nuclear polarization (DNP) technique [40]. By microwave irradiation, DNP transfers a fraction of the high electronic polarization in paramagnetic centers to the target nucleus. The paramagnetic centers were created by electron bombardment of frozen ammonia [41]. The measured A_y were consistent with zero in contrast to the predicted large A_y values [8]. This result came as a surprise at a time when it was thought that π-nucleus scattering was reasonably well understood.

In the p-shell model the ground state of ^{15}N is described by a proton hole in a closed p-shell. The magnetic moment ($-0.283\ \mu_N$) of the g.s. of ^{15}N is in good agreement with the Schmidt value ($-0.263\ \mu_N$) and the monopole form factor from electron scattering is reproduced by the p-shell model as well as by large-space shell model calculations. (See, for example, Ref. [42]). However, the q-dependence of M_{T} is only poorly described by the p-shell model. The same (spin-dependent) nuclear matrix elements, with $A_{J(KS)} = A_{1(01)}$ being predominant, enter the calculation of M_{T} as that of $\mathcal{G}$ for pion scattering. Thus, any deficiency of the structure model in reproducing M_{T} also casts doubt on the validity of predictions of A_y.

In the calculation of A_y [8] for ^{15}N, the spin-dependent matrix elements were renormalized so that M_{T} was fitted in the region of its maximum, that is, at values of q where most of the pion data were taken. The A_y with these modified matrix elements are very large when the ρ^2 term is used but only half as large without that term. Neither prediction agrees with the data which are consistent with zero at all angles.

Use of matrix elements from large space shell model calculations [43] fits M_{T} to about $q = 2.4$ fm^{-1}. Large incident-energy dependent effects from the $2\hbar\omega$ components on the cross section for $^{15}\mathrm{N}(\pi^-, \pi^0)$ SCX have been predicted [42] but there are no experimental data. Calculations of A_y with these matrix elements for comparison with the elastic π^+ data [7] are not available yet.

3.2. Elastic scattering and SCX on ^{13}C

Angular distributions of A_y for $^{13}\mathrm{C}(\pi, \pi)$ elastic scattering were measured [9, 10] at LAMPF at 130 and 230 MeV and at two fixed momentum transfers at energies across the Δ resonance. The cryogenic target [3, 4] used ^{13}C-enriched 1-butanol ($CH_3(CH_2)CH_2OH$) doped with a paramagnetic chromium-V complex to provide the free electrons for DNP employing microwave irradiation. Typical polarizations were 30%. The A_y for π^+ and π^- elastic scattering at 130 MeV are shown in Fig. 1.

The theoretical curves in Fig. 1 were obtained with the multiple scattering code PIPIT [33] combined with a modified version of the inelastic scattering code ARPIN [12, 38]. The solid lines are predictions [9, 10] with the amplitudes of Ref. [38]. Another set of amplitudes had been constructed [44] by modifying the 1(01) and 1(21) amplitudes of Ref. [38] to fit M_{T} to higher q, the magnetic moment of the g.s. of ^{13}C, the β decay constant of ^{13}N and the cross sections for the $^{13}\mathrm{C}(\gamma, \pi^-)$ reaction.

The A_y with these modified amplitudes (dashed lines) are out of phase with the predictions using the original p-shell densities. This sign reversal was traced [10, 13] to the drastic modification [44] of the quadrupole spin flip ($J(KS) = 1(21)$) part to which A_y is very sensitive. Little is known about the 1(21) amplitude from other experiments. Ref. [13] obtained a better representation of the A_y between 50 and 90° than Ref. [10] but also failed in reproducing the measured values near 100°.

Attempts were made [8, 10] to calculate A_y by including phenomenological $2\hbar\omega$ components [45] that fit the magnetic form factor better at large q. However, none of the calculations reproduce the A_y data satisfactorily. The strong sensitivity of A_y for elastic scattering from p-shell nuclei

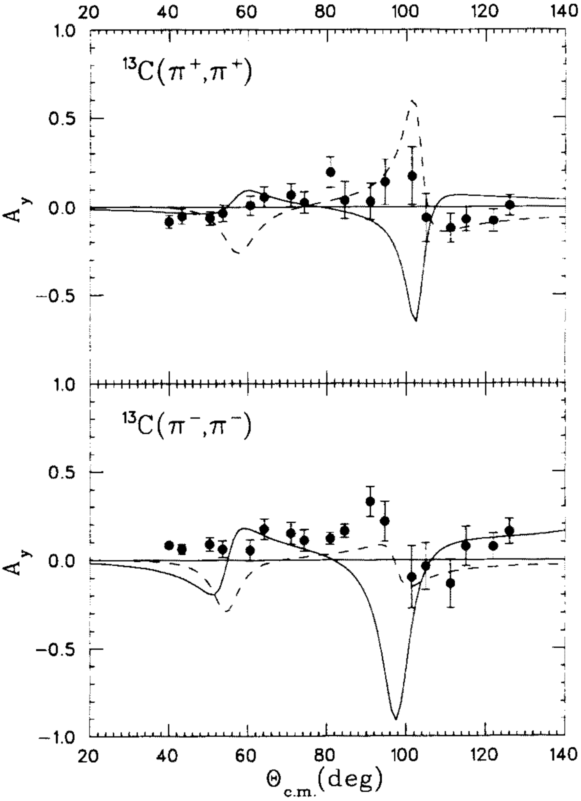

Fig. 1. Asymmetries for elastic scattering of π^+ and π^- from ^{13}C at 132 MeV. (From Ref. [10]).

to the nuclear structure details demonstrates that valuable information on the spin-dependent parts of the g.s. density is contained in the data which, however, cannot be extracted until the reaction mechanism is understood better. We note that theory [13, 14] has been more successful in reproducing the A_y [11] for the SCX reaction $^{13}C(\pi^-,\pi^0)^{13}N$. However, none of the calculations fit the $A_y \approx 0$ from SCX between 50° and 60°.

4. Results for ^{3}He

Differential cross sections for π elastic scattering from mass-3 nuclei have been studied for some time, both experimentally and theoretically (see references in Ref. [18]). The first model calculations of asymmetries were made about 20 years ago [34, 46] but measurements of asymmetries have become possible only recently. ^{3}He has attractive features for a study of spin-dependent effects in π-nucleus scattering. Reliable wave functions have been obtained for ^{3}He by Faddeev calculations [47, 48] so that the spin-dependence of the π-nucleus interaction can be investigated without large uncertainties in the nuclear structure. The small number of nucleons should eventually make full microscopic calculations possible.

To lowest order, the spin-dependent scattering amplitude $\mathcal{G}$ arises only from scattering by the single neutron which determines to about 90% [47, 48] the spin of ^{3}He. However, A_y involves both $\mathcal{F}$ from coherent scattering from all nucleons and $\mathcal{G}$ from scattering from the single neutron. Thus A_y for $\pi-{}^3$He scattering are expected to be very different from A_y from elementary π-neutron scattering.

In contrast to elastic scattering, the $^3\mathrm{He}(\pi^-,\pi^0)^3\mathrm{H}$ SCX reaction involves only one nucleon in ^{3}He in lowest order. Since the pion has no spin it cannot induce a true spinflip of the nucleus or nucleon it interacts with. Thus the SCX process on ^{3}He with spin up can occur only on that proton whose spin is down so that the neutron from the SCX process couples with the spin-up neutron to spin $s = 0$. Indeed, at far forward angles, where multiple scattering effects are expected to be small, all theoretical curves approach the negative of the elementary $p(\pi^-,\pi^0)n$ asymmetry. (See below).

4.1. π^+ and π^- elastic scattering on ^{3}He

Measurements of A_y with π^+ and π^- on polarized ^{3}He were made first at TRIUMF [16] at 100 MeV using the high-density, optically pumped ^{3}He gas target that had been developed there [5]. The gas was contained at a pressure of about 6 atm. in cylindrical glass cells with thin-walled hemispherical endcaps through which the pion beam entered and exited. Very large values of A_y were found for π^+ and reproduced quite well by a simple schematic model [17] that neglects multiple scattering and includes only the s-state part of the ^{3}He g.s. wave functions. Multiple scattering effects are relatively small at 100 MeV but their inclusion improves the fit to the data. However, multiple scattering is predicted [18] to cause a change in A_y from large positive to large negative values as the energy is increased from below to above the Δ resonance. This sign change does not appear in the schematic model. At energies ≥ 250 MeV, the small components in the ^{3}He wave function become important.

Thus measurements of π^+ elastic scattering from polarized ^{3}He at energies near the centroid and above the Δ resonance were of great interest. This motivated moving the TRIUMF target to the P^{3}E area at LAMPF where high beam fluxes were available across the region of the Δ resonance. Diode lasers were added [49] to the optical pumping system during the experiment. Target polarizations ranged from 30% to 50%. The direction of the polarization was switched from "up" to "down" every 11 minutes in order to minimize systematic uncertainties. Polarizations, $p = p \downarrow = p \uparrow$ were measured periodically, in about 8 hour intervals. The scattered π were detected with the Large Acceptance Spectrometer (LAS) [50].

Spin-up and spin-down spectra (Fig. 2) for π^+ scattering were measured [19] between $\theta_{\rm lab}$= 50° and 100° at incident energies T_π = 142, 180, and 256 MeV. The values of A_y (Fig. 3) were obtained from the yields in the peak at Q = 0. Background events from the glass target cell were reduced quite efficiently by software cuts on information obtained from wire chambers located between the quadrupoles and the dipole of the LAS. The remaining background was subtracted using spectra taken with an evacuated target cell. The background cancels when taking the difference of the up and down spectra but needs to be subtracted when taking the sum.

At 142 and 180 MeV the data display negative asymmetries near 60° which were completely unexpected. There is also a shift in the position

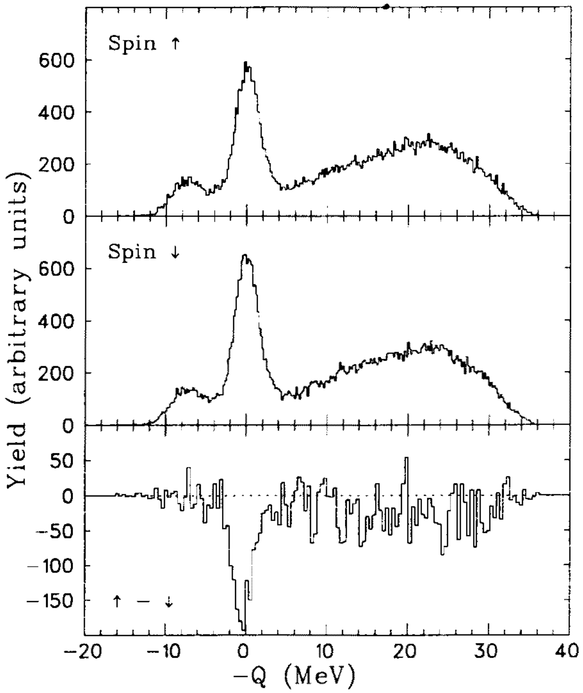

Fig. 2. π^+ spectra [19] from the polarized ^{3}He target at T_π = 180 MeV and $\theta_{\rm lab}$ = 50°. Top (center): target spin parallel (antiparallel) to the normal to the reaction plane. Bottom: difference spectrum.

of the positive maximum to a larger angle than predicted. The A_y from conventional multiple scattering [18] (solid lines) or DWIA approaches [12, 13] are positive at all measured angles at 142 and 180 MeV. At 256 MeV the experimental A_y are negative at all angles in agreement with theory. The sign change of A_y between 180 and 256 MeV is caused by multiple scattering. The inclusion of a purely scalar ρ^2 term at 180 MeV gives A_y out of phase with the data.

The unexpected negative A_y near 60° and the shift in the position of the positive maximum at 142 and 180 MeV were reproduced quite well (dashed lines) by a model that invokes a large second-order contribution to $\mathcal{G}$ from the Δ^{++}-neutron spin-spin interaction [19, 51]. This model uses the $\mathcal{F}$ and $\mathcal{G}$ from the full multiple scattering calculations [17, 18] with Faddeev wave functions for ^{3}He. A contribution from the Δ^{++}-neutron spin-spin interaction, calculated in the PWIA using a pure *s*-state wave function for ^{3}He, is added to $\mathcal{G}$. The incident π^+ forms a Δ^{++} with one of the two protons and the Δ^{++} then interacts with the polarized neutron. The fit to A_y with this hybrid model is excellent at 180 MeV. At 142 MeV the asymmetry near 60° is not quite as negative as in the experiment. At 256 MeV the hybrid model gives a better description of the angular distribution than the conventional calculations. Improved fits to the A_y (and the differential cross sections) at 142 and 256 MeV A_y were obtained [19] (Fig. 3, dash-dotted lines) by calculating the first-order $\mathcal{F}$ and $\mathcal{G}$ from π-nucleon phase shifts evaluated at an energy 15 to 20 MeV lower than the incident pion energy (energy shift $\mathrm{E_{sh}}$). We note that an energy shift alone does not create the negative A_y near 60° at 142 and 180 MeV.

The hybrid model predicts that the Δ-neutron spin-spin interaction affects the A_y for π^- scattering much less than for π^+ scattering since the first-order $\mathcal{G}$ is much larger for π^--neutron than π^+-neutron due to the different isospin coupling coefficients at the π-nucleon-Δ vertex. Thus the second-order term in π^- scattering is smaller relative to the first-order term whereas in π^+ scattering they are comparable.

In order to test this model prediction π^- data were taken [19, 20] recently. Indeed, the π^- data (Fig. 3, bottom panel) do not exhibit the negative A_y near 60° which were so unexpected for π^+. The A_y from the conventional and the hybrid models do not differ very much from each other but both give A_y values about a factor of two too small. A DWIA calculation [52] (dotted line) reproduces the magnitude of the π^- data better but gives too small values for π^+ (not shown).

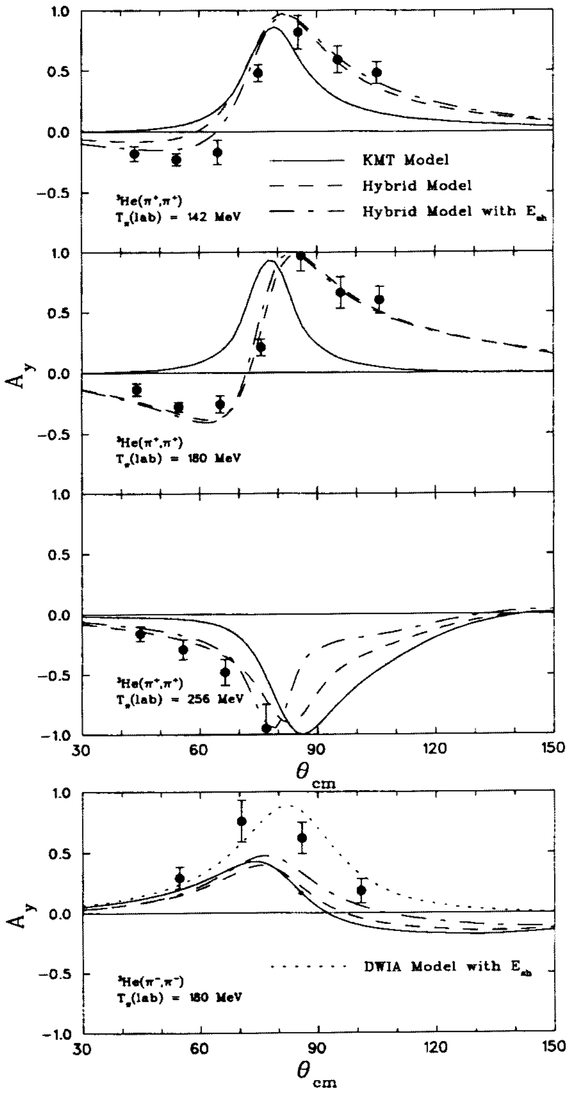

Fig. 3. Asymmetry angular distributions for elastic scattering of π^+ (top three panels) and π^- (bottom panel) from polarized ^{3}He. Data of Ref. [19, 20]. See text for theoretical curves.

4.2. The $^3He(\pi^-, \pi^0)^3H$ reaction

The single-charge-exchange (SCX) reaction isolates the isovector parts of the scattering amplitudes. Although a measurement of both π^+ and π^-

scattering contains the isovector in addition to the isoscalar information, a SCX measurement which is unmasked by Coulomb scattering is very desirable. Asymmetries from the ^{3}He$(\pi^{-},\pi^{0})^{3}$H reaction on polarized ^{3}He were measured [21] using a stripped-down version of the recently developed Neutral Meson Spectrometer (NMS) [53] to detect the neutral pions. For best resolution (of the order of 1 MeV), the NMS requires the position of the interaction vertex in the target to be known to a few mm.

However, to attain a gaseous target of sufficient areal density a spherical glass cell of 3.5 cm diameter (and 110-μm wall thickness) was made and filled with ^{3}He at a pressure of 4 atm. This limited the π^{0} energy resolution to about 10 MeV (FWHM). In addition, to achieve a sufficiently large solid angle, only the 60 CsI crystals in each of the two arms of the NMS and the charged-particle veto detectors were used (Fig. 4). This resulted in an overall energy resolution width of about 22 MeV which was, of course, not sufficient to resolve ^{3}He$(\pi^{-},\pi^{0})^{3}$H events from the breakup continuum.

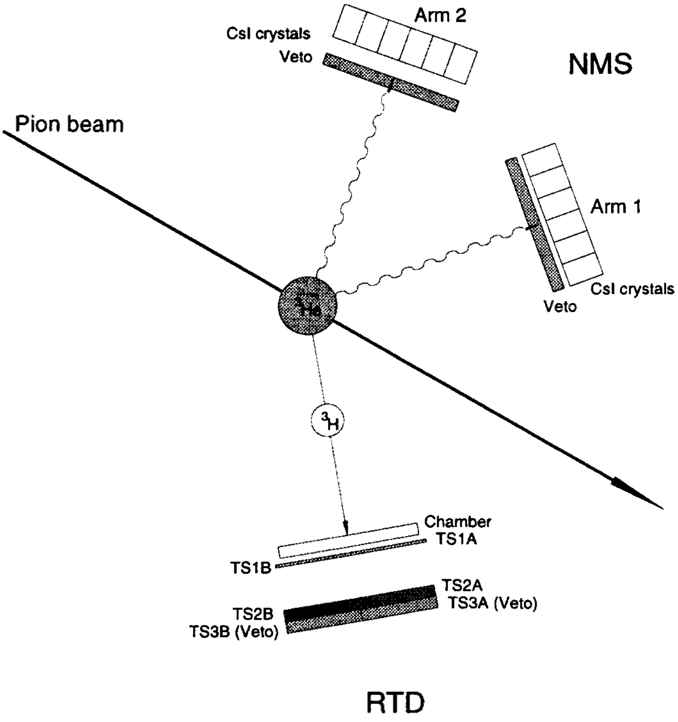

Fig. 4. Sketch of setup for π SCX experiment ^{3}He$(\pi^{-},\pi^{0})^{3}$H. (From Ref. [21]).

In addition, it was not possible to reject events from the glass cell as was done in the elastic scattering experiments. The large background of π^{0} from the glass was eliminated successfully by detecting the residual tritons with a recoil-triton detector (RTD) (Fig. 4) in coincidence with the NMS. This detector consisted of a wire chamber followed by three sets of two adjacent scintillators.

The wire chamber determined the direction into which the recoil particle was emitted and thus allowed one to take advantage of the coplanarity of the two-body reaction $^3\mathrm{He}(\pi^-,\pi^0)^3\mathrm{H}$. Events from three-body reactions such as $^{28}\mathrm{Si}(\pi^-;\pi^0,\mathrm{t})^{25}\mathrm{Mg}$ from the glass were effectively rejected. The scintillators allowed an identification of tritons by a combination of energy-loss and time-of-flight information. Large values of A_y were observed (Fig. 5).

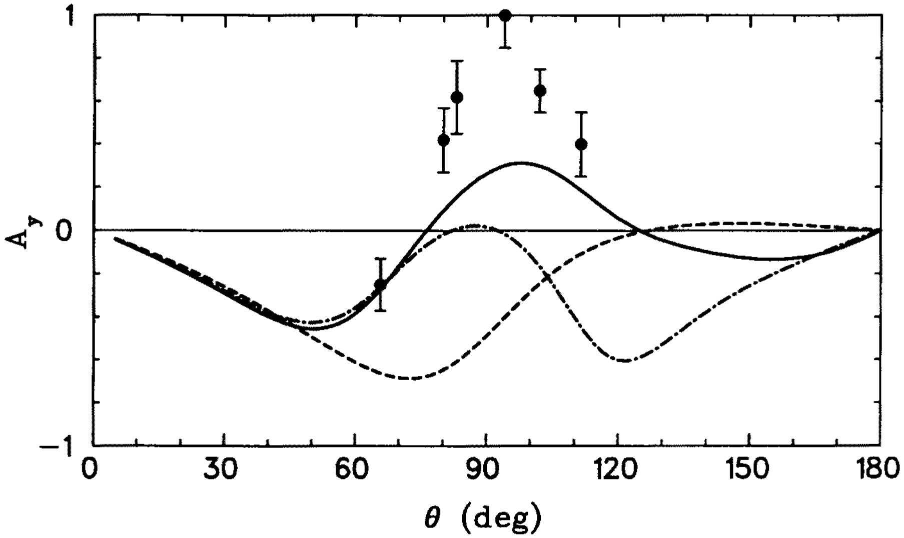

Fig. 5. Preliminary asymmetry data for $^3\mathrm{He}(\pi^-,\pi^0)^3\mathrm{H}$ at T_π = 200 MeV [21].

The A_y from SCX on polarized $^3\mathrm{He}$ is predicted to equal the negative of the elementary A_y from $p(\pi^-,\pi^0)n$ at forward angles (dashed lines). However, there are very large differences between the (negative) elementary A_y and the model calculations beyond 60° where multiple scattering and possibly two-nucleon correlations [54] affect the asymmetry strongly. None of several attempts to reproduce these data has succeeded thus far [52, 55]. The result of a DWIA calculation [55] with rescattering is shown as the dash-dotted line. Inclusion of two-nucleon correlations [54] led to the solid line. A simple DWIA calculation [52] (not shown) gives a curve similar to the solid line. Calculations with the hybrid model are not available yet.

5. Conclusion

Experimental A_y from elastic π scattering and SCX on p-shell nuclei of spin 1/2 contain information on the spin-dependent parts of the g.s. densities. However, because the π-nucleus interaction is not sufficiently well understood this information cannot be extracted at present. Recent A_y data for elastic scattering and SCX on polarized ^{3}He appear to provide the key for a better understanding of the spin-dependent parts of the π-nucleus interaction. As the incident energy is passing through the region of the Δ resonance, the data display the features expected from multiple scattering. In addition, there is evidence for a Δ-neutron spin-spin interaction from the observation of unexpected negative asymmetries in π^+ scattering at forward angles at 142 and 180 MeV.

Many thanks to M.E. Espy and Q. Zhao for permission to present some of their thesis data prior to publication. Thanks also to Drs. C. Bennhold, S.S. Kamalov, and W.R. Gibbs for helpful discussions and for making theoretical predictions available prior to publication. The recent work at LAMPF would not have been possible without the unrelenting support of Dr. R. L. Boudrie and the expertise of Dr. J.M. O'Donnell. This work was supported by the U. S. Department of Energy and the Graduate School of the University of Minnesota.

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